

Quenching Star Formation: Can AGN Do the Trick?

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Abstract. We post-process galaxy star formation histories in cosmological hydrodynamics simulations to test quenching mechanisms associated with AGN. By comparing simulation results to color-magnitude diagrams and luminosity functions of SDSS galaxies, we examine whether “quasar mode” or “radio mode” AGN feedback can yield a realistic red sequence. Both cases yield red sequences distinct from the blue cloud, decent matches to the luminosity function, and galaxies that are too blue by about 0.1 magnitudes in $g - r$. Our merger-based prescription for quasar mode feedback, however, yields a red sequence build-up inconsistent with observations: the luminosity function lacks a characteristic knee, and the brightest galaxies include a small number of young stars.

Keywords: Galaxy evolution; Active Galactic Nuclei feedback

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INTRODUCTION

Recent research has linked active supermassive black holes to the evolution of galaxies and clusters, both observationally via the $M_{\text{BH}}-\sigma_{\text{bulge}}$ relation, and theoretically to solve the cooling flow and star formation quenching problems. Whether AGN can inject enough energy into the right gas at the right place and time on galactic scales remains a contentious question. But when AGN are invoked in theoretical studies, do they have the desired *effects* in detail? If we assume that the physics of feedback works on small scales, do we reproduce the correct distributions of galaxy and inter-galactic medium properties?

In this work, we approach this question in terms of galaxy properties. We test how AGN feedback impacts two observations: a) the bimodality of galaxy colors, with a tight red sequence, a diffuse blue cloud, and a discernible gap in between; and b) the galaxy luminosity function with a characteristic knee at $r \simeq -20.77$, with red galaxies dominating the bright population and blue galaxies dominating the faint one [1]. The color bimodality requires star formation to cease in less than 1 Gyr as a galaxy moves from blue to red. The knee in the luminosity function specifies a characteristic luminosity or mass scale above which galaxies tend to stop forming stars. AGN feedback in different contexts could drive these phenomena by quenching star formation.

Two independent “modes” of AGN feedback have emerged as potential star formation quenching mechanisms. High luminosity AGN or quasars resulting from galaxy mergers may be able to expel the cold gas from a galaxy and prevent future star formation (“quasar mode feedback”). On the other hand, low luminosity radio AGN embedded in massive galaxies may inject energy into their hot X-ray gas halos, preventing the gas

from cooling and forming stars [2].

We test these mechanisms of star formation quenching using post-processing techniques on cosmological hydrodynamics simulations.

ANALYSIS: SIMULATIONS AND POST-PROCESSING TECHNIQUES

We develop and apply a new set of post-processing routines to existing cosmological simulations. We have simulated a Λ CDM volume of $(48h^{-1})^3 \text{ Mpc}^3$ with 256^3 dark matter + 256^3 gas particles using a modified version of GADGET-2, a smoothed-particle hydrodynamics code [3]. This choice of volume gives a gas particle mass of $\sim 10^8 M_\odot$, and a galaxy mass resolution of $\sim 7 \times 10^9 M_\odot$. Our version of GADGET-2 dynamically incorporates analytic sub-resolution models for star formation, feedback from star-formation driven winds, and chemical enrichment [4, 5]. Simulation outputs consist of a snapshot of the simulated volume at each of 100 redshifts from $z = 30$ to $z = 0$.

With our new post-processing routines, we mimic the effects of different quenching mechanisms by applying simple prescriptions to the resulting galaxy star formation histories. As an example, consider quenching due to merger-induced quasars. We simplify this to a quenching criterion: any (resolved) galaxies that are the remnants of major (3:1 mass ratio or smaller) mergers should not form any new stars. We identify major mergers in the simulation outputs as those galaxies whose stellar mass has grown by at least a factor of $(1 + 1/3)$ from one time step to the next (~ 300 Myr for $z < 1$). A merger remnant remains flagged as such for all later time steps unless it is subsumed by another more massive galaxy. We then step through each time step starting at $z \sim 10$ and determine whether each star particle that formed within the last time step formed within a merger remnant. If so, then we flag that star particle as quenched: it should never have formed. Then, when we compute stellar masses or luminosities of galaxies, we just *ignore* those star particles that we flagged as quenched.

For radio mode quenching we follow an analogous prescription. Here, the quenching condition derives from the characteristic minimum dark matter halo mass required for a stable hot gas halo, $M_{\text{halo}} \sim 10^{12} M_\odot$. We assume that no new stars can form within halos above this critical mass because the AGN prevents the hot gas halo from cooling.

RESULTS

In Figure 1 we compare color-magnitude diagrams (CMDs) and luminosity functions (LFs) of our simulation quenching models to data from the Sloan Digital Sky Survey (SDSS) Value-Added Galaxy Catalog (VAGC) low-redshift sample [6]. The left column results from our radio mode quenching mechanism, which is keyed to the critical dark matter halo mass, $M_{\text{halo}} = 10^{12} M_\odot$, while the right column results from our quasar mode mechanism based on galaxy mergers.

Both star formation quenching mechanisms successfully produce a bimodality in galaxy colors, whereas simulations without quenching produce only star-forming blue

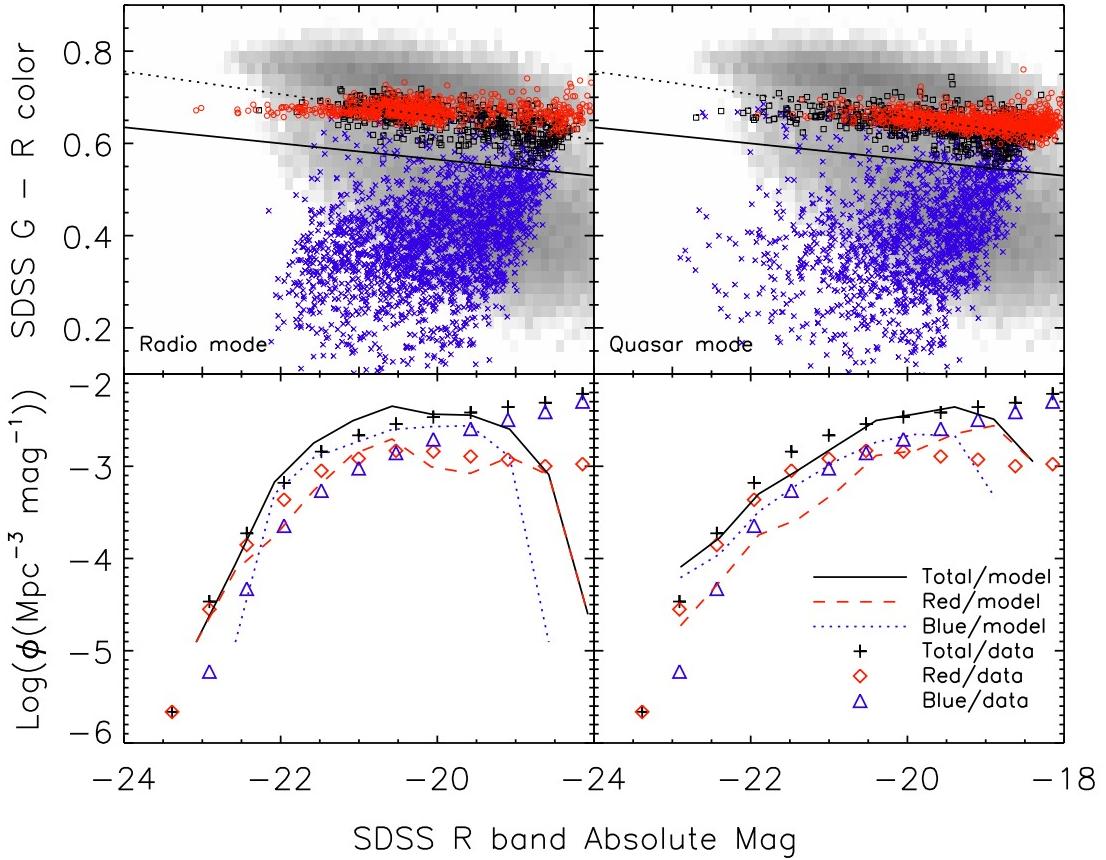


FIGURE 1. Color-magnitude diagrams and luminosity functions for our simulations with quenching prescriptions applied. Top panels compare our simulated CMDs (symbols) to the low-redshift CMD of the SDSS VAGC (gray shading). Galaxy symbols are coded by the age of the youngest star particle: 0–1 Gyr (blue x’s), 1–4 Gyr (black squares), and > 4 Gyr (red circles). We include lines separating blue and red galaxy loci (solid lines for simulation CMDs, and dotted lines for real galaxies). Bottom panels split luminosity functions into blue galaxies (dotted line/triangles), red galaxies (dashed line/diamonds), and all galaxies (solid line/plusses) for both simulated (lines) and real (symbols) galaxies. Our mass resolution limit, manifest as a diagonal envelope on the right side of the LFs, corresponds roughly to $r = -20$ in the LFs.

galaxies (including ones brighter than $r \simeq -24$; not shown). The separation between blue and red galaxies for the simulations (solid line), however, is bluer than that for real galaxies (dotted line) by about 0.1 magnitudes in $g - r$. This problem most likely arises because our simulated galaxies are more metal poor than real galaxies, which may reflect uncertainties in yields or stellar population synthesis models.

We do not include the effects of dust, which we will explore in greater detail in the future. Dust extinction moves simulated blue galaxies up and to the right in the CMDs, perhaps contaminating the red sequence with a small population of dusty galaxies.

Quasar mode and mergers: the wrong red sequence

The red sequence driven by galaxy mergers fails to reproduce key characteristics of the observed red sequence in subtle ways. While the overall shape of the luminosity function matches reasonably well, this quenching mechanism produces slight excesses of galaxies at both the faint and bright ends. Furthermore, merger quenching yields an underabundance of red galaxies around M^* , leading to a flatter bright-end slope. Basically, the spread in merger masses does not yield a sharp knee at M^* . The growth of the red sequence suggests additional conflicts with observation: the brightest galaxies include a population of young stars, acquired via recent merger events with younger galaxies. These trace young stellar populations do not appear in observed bright red sequence galaxies [7].

Radio mode and hot halos: the right red sequence?

The red sequence driven by hot gas halos that never cool to form stars shows better overall agreement with the observed luminosity function. Further, galaxies *at all epochs* tend to migrate to the red sequence at a rough characteristic absolute magnitude ($r \sim -21$) directly related to the critical halo mass, $10^{12}M_\odot$. Although variations in the assembly histories of galaxies in halos of a given mass smear out this characteristic crossing magnitude, the critical halo mass directly gives rise to the knee in the luminosity function. The M^* population of red galaxies continues to grow at $z = 0$ as more galaxies end up in massive halos, while the brightest red galaxies have grown mostly via minor dry mergers over billions of years.

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REFERENCES

1. M. R. Blanton, R. H. Lupton, D. J. Schlegel, M. A. Strauss, J. Brinkmann, M. Fukugita, and J. Loveday, *ApJ* **631**, 208–230 (2005), arXiv:astro-ph/0410164.
2. D. J. Croton, V. Springel, S. D. M. White, G. De Lucia, C. S. Frenk, L. Gao, A. Jenkins, G. Kauffmann, J. F. Navarro, and N. Yoshida, *MNRAS* **365**, 11–28 (2006), arXiv:astro-ph/0508046.
3. V. Springel, *MNRAS* **364**, 1105–1134 (2005), arXiv:astro-ph/0505010.
4. V. Springel, and L. Hernquist, *MNRAS* **339**, 289–311 (2003), arXiv:astro-ph/0206393.
5. B. D. Oppenheimer, and R. Davé, *MNRAS* **387**, 577–600 (2008), 0712.1827.
6. M. R. Blanton, D. J. Schlegel, M. A. Strauss, J. Brinkmann, D. Finkbeiner, M. Fukugita, J. E. Gunn, D. W. Hogg, Ž. Ivezić, G. R. Knapp, R. H. Lupton, J. A. Munn, D. P. Schneider, M. Tegmark, and I. Zehavi, *AJ* **129**, 2562–2578 (2005), arXiv:astro-ph/0410166.
7. P. Sanchez-Blazquez, B. K. Gibson, D. Kawata, N. Cardiel, and M. Balcells, *ArXiv e-prints* (2009), 0908.2548.